

QCD FROM SHORT DISTANCES TO LONG

QM2001

Pre-Conference
Symposium

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• Paradox of QCD

- Observed states: hadrons

- Rules: for q, G

$$\mathcal{L}_{QCD} = \bar{q}(i[\gamma \cdot \partial - ig\gamma \cdot A] - m)q$$

$$- F^{\mu\nu}[A]F_{\mu\nu}[A]$$

$$\hookrightarrow \partial^\mu A^\nu - \partial^\nu A^\mu + g[A^\mu, A^\nu]$$

• The other field:

$$EoM: \gamma \cdot D[A] q = 0$$

$$D_\mu F^{\mu\nu} = 0$$

$$D_\mu = \partial_\mu - ig A_\mu$$

$$n^\mu D_\mu[A] \bar{\Phi}(x) = 0$$

$$\bar{\Phi}_c(x, x_0) = P \exp(ig \int_{x_0}^x dn_c \cdot A)$$

$$\int_x^{x_0} n_c(x) = n$$

- path ordered exponential

- nonabelian phase

- Wilson line

- Polyakov line

- link (lattice)

C straight: recoil-less source of gluons
(high-energy or heavy quark)

- QCD as a
FIELD THEORY

- States: $n(k_1, k_2, \dots)$
variable occupation numbers

- Rules for $\langle n'(t'), | n(t) \rangle$

- Renormalizable FT: all transitions computable in terms of couplings \leftrightarrow elementary transitions

$$\langle g(t'), | g(0) \rangle \sim \frac{g(t')}{g(0)}$$

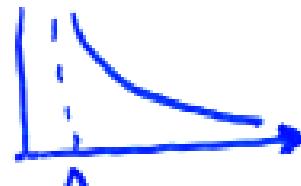
- Can compute

$$t' \frac{d}{dt}, g(t') = -\beta(g(t'))$$

- In QCD

$$g(t') \xrightarrow[t' \rightarrow 0]{} 0 \quad g(\mu) \xrightarrow[\mu \rightarrow \infty]{} 0$$

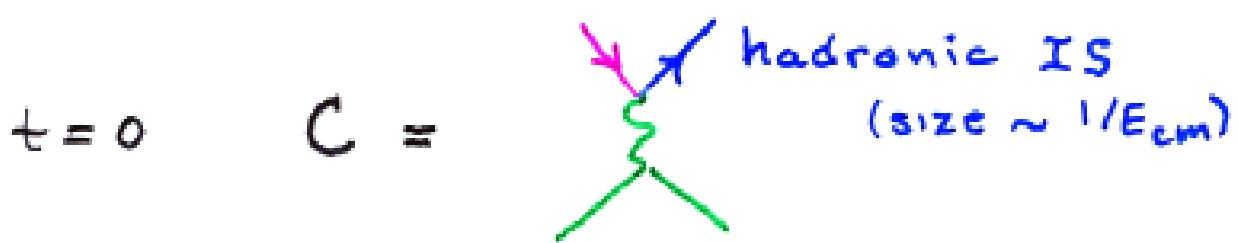
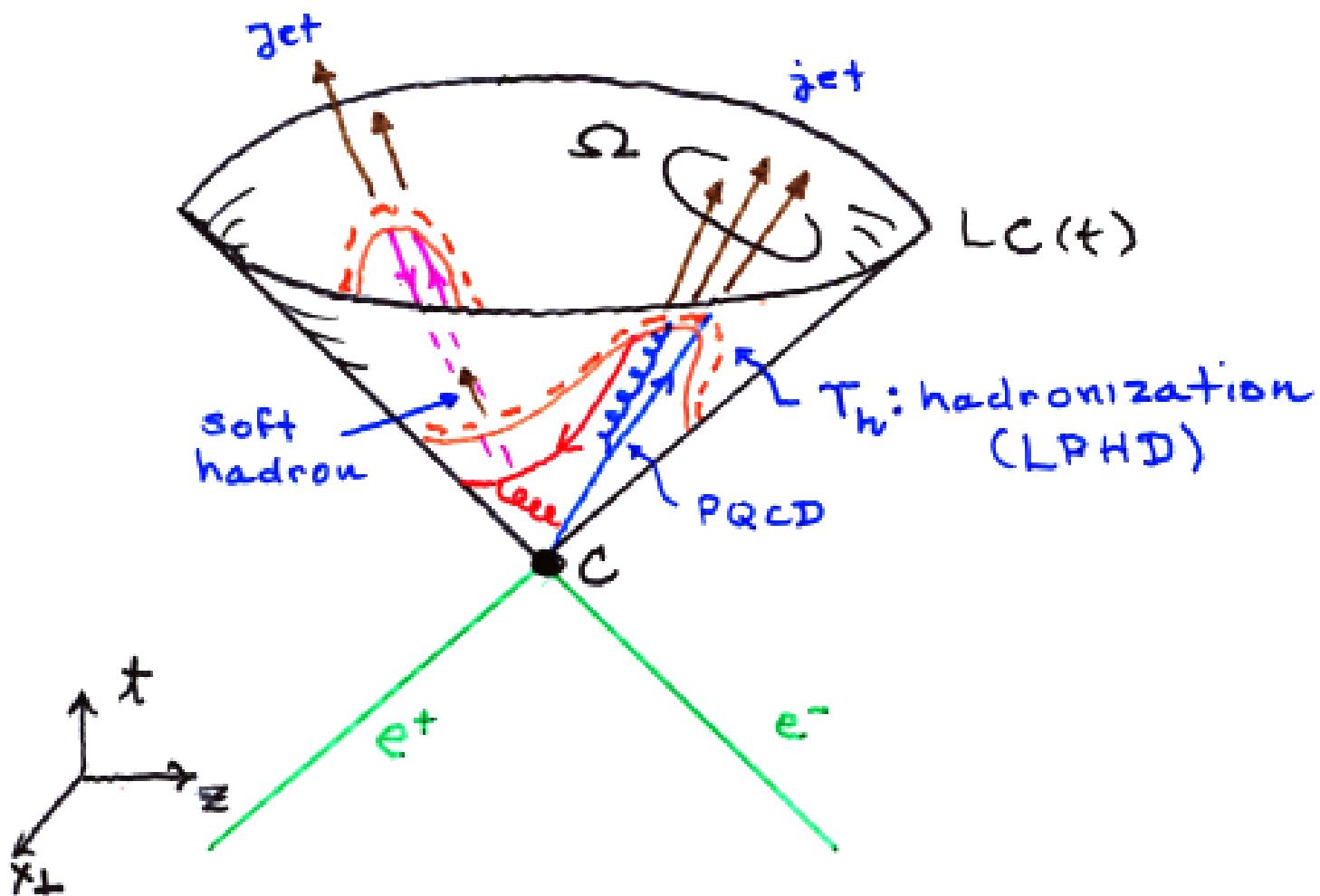
$$g_{\mu\nu}^2 = \frac{12\pi}{b_0 \ln \frac{\mu^2}{\Lambda_{QCD}^2}}$$



asymptotic freedom Λ_{QCD} μ

- How to 'observe' quarks/gluons?
- How to 'resolve/explore' paradox

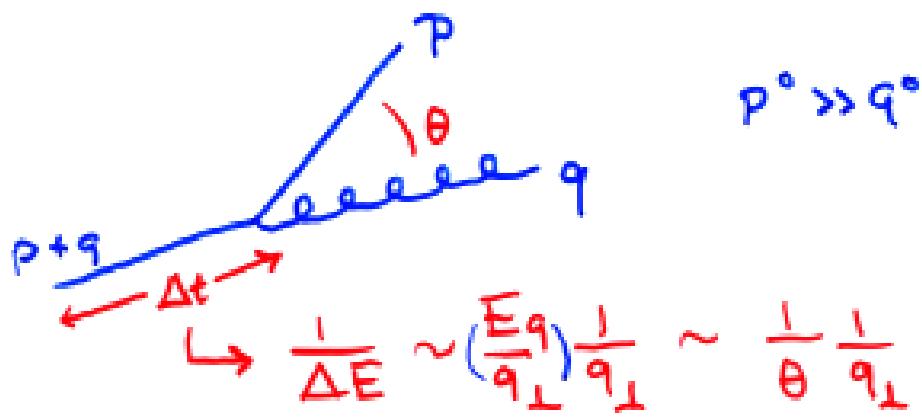
$e^+e^- \rightarrow \text{Hadrons} : \text{Seeing Quarks and Gluons}$



$T_h > t > 0$: pQCD for inclusive cross sections

$$\alpha_s(E_J) \xrightarrow{\sigma_{\text{Jet}}(\Omega, E_{\text{jet}})} \Delta_{\text{QCD}} \quad \begin{aligned} \text{Infrared Safety} \\ = \sum_n c_n(\Omega) \alpha_s(E_{\text{jet}}) \end{aligned}$$

- $\Theta_{\text{Jet}-e} \rightarrow \text{spin}(q) = \frac{1}{2}$, $3J \rightarrow qq$ coupling, $4J \rightarrow gg$...
- T_h and formation time



- Small angles, long times
- Large angles, small times

- Jets spacelike separated } importance
→ LPDH of light quarks
- T_h fixed proper time } $m_{u,d} \ll \Lambda_{\text{QCD}}$
- $t > T_h$: mesons baryons
 - large- t excitations of QCD ground state.
 - Chiral symmetry breaking (χSB)
 - Confinement
 - light modes in QCD vacuum

XSB : The QCD Vacuum

XS: Two light quarks:

$$\overbrace{u \ d} \quad (u' d') = U \begin{pmatrix} u \\ d \end{pmatrix}$$

Isospin

$$L_{QCD}(u', d') = L_{QCD}^{(u, d)} \rightarrow I^2, I_3 \text{ label states}$$

Extra: if $m_u = m_d = 0$

$$L_{QCD}(u, d) = L_{QCD}^{(u_L, d_L)} + L_{QCD}^{(u_R, d_R)}$$

$$L_{QCD}(u'_{L,R}, d'_{L,R}) = L_{QCD}^{(u_{L,R}, d_{L,R})}$$

$$L/R: \uparrow \nearrow^P = \frac{s}{R} + b \downarrow \nearrow^P$$

Should have $I^2_{L,R}, I_3_{L,R}$

Why not?

(m_u, m_d 'small'? Would still have approximate symmetry ...)

XSB: Ground State Condensate
of quark pairs!

$$\langle 0 | \bar{u}_R u_L + \bar{d}_L d_R | 0 \rangle = \sum e^{\frac{i\phi_u}{2}}$$

order parameter

$\Sigma = 0$ in PT:

$$= 0$$

$g_{u,d}$: new degrees of freedom

Spontaneous Symmetry Breaking

Isospin-invariant effective L

$$U = \exp^{i\pi_i \sigma_i / 2f_\pi}$$

π_i : pion fields!

$$\mathcal{L}_{\text{eff}} = \frac{f_\pi^2}{4} \text{Tr} (\partial_\mu U^\dagger \partial^\mu U) \sim \partial_\mu \pi^a \partial^\mu \pi^a + \dots$$

\uparrow pion K.E.

$$+ \sum \text{Re} \{ \text{Tr} M U^\dagger \} + \dots$$

$\uparrow (m_u \quad 0)$
mass for pions
 $\rightarrow 0$ for $m_{u,d} = 0$

* Low-E: lowest derivatives only

* I-inverse forces form of \mathcal{L}_{eff}

* Experiment \Rightarrow Complex Ground State
 \Rightarrow Values $m_{u,d} \sim \text{MeV}$

- $m_\pi \sim 10^2 \text{ MeV}$
 $\hookrightarrow m_{u,d} \sim 5-10 \text{ MeV} \ll \Lambda_{\text{QCD}} \sim 200 \text{ MeV}$
hadronization
- Current vs Constituent Quarks
 ↓
 PT and L_{eff}
 $m_{u,d} \sim \text{MeV}$
(elementary)
- Quark model
 $m_{u,d} \sim 10^2 \text{ MeV}$
(collective)
- u,d,s
 $SU(2) \rightarrow SU(3)$
- Dynamics of the vacuum

Instantons

and

CP violation

Why not? The mystery of QCD

$$\mathcal{L}_{\text{eff}} = \frac{f_\pi^2}{4} + r(\omega_\mu U^\dagger \partial_\mu U) + \sum R \text{tr}(M U^\dagger)$$

$$- \frac{\chi}{2} (\theta + i \log \det U)^2$$

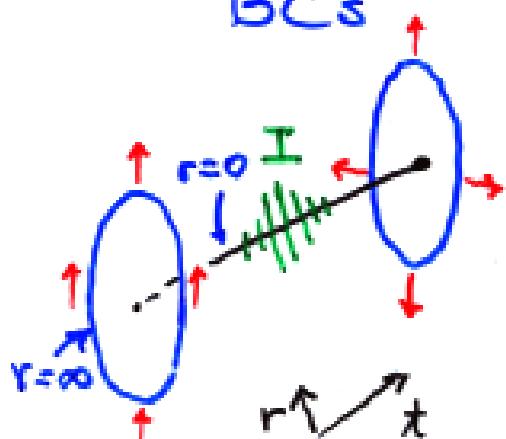
↑ relative phase $\rightarrow \phi$

Why is $\theta=0$ @ $T=0$?

Could it be $\neq 0$ at any T, B ?

• Instantons

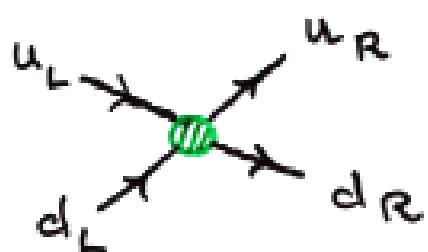
- $E_{\text{color}} = B_{\text{color}} = 0 \rightarrow$ gluon field unobservable phase
- But: phase \mapsto inequivalent BC at $r = \infty$
- Instanton: tunneling event between inequivalent BCs



• Instantons couple to quarks!

$$\mathcal{L}_I = G [(\bar{q} \sigma^- q)^2 + (\bar{q} \sigma^+ q)^2]$$

$q = \begin{pmatrix} u \\ d \end{pmatrix}$

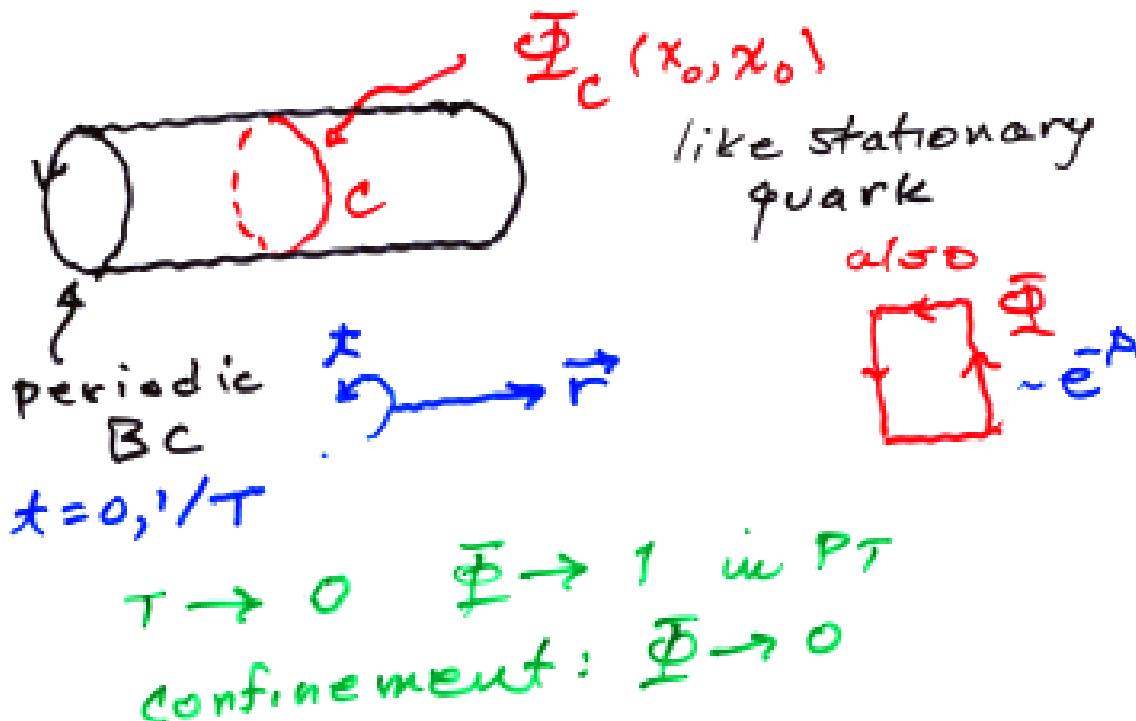


breaks χS !

model for π, N (instanton liquid)

- Confinement

- distinct from XSB
- subtle with light quarks
- order parameter vs T :

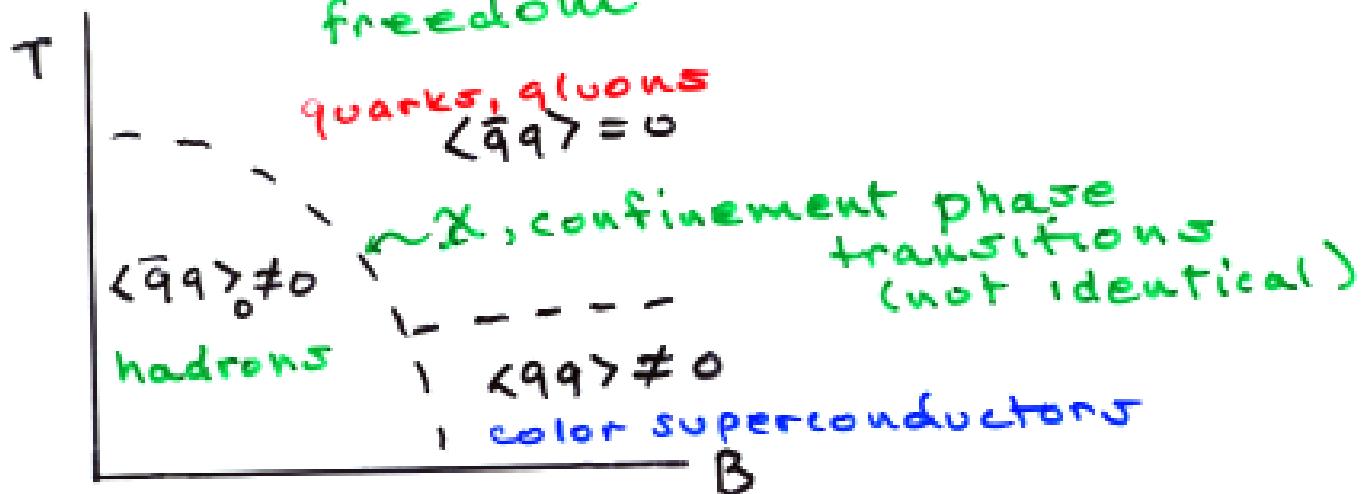


- Lattice studies

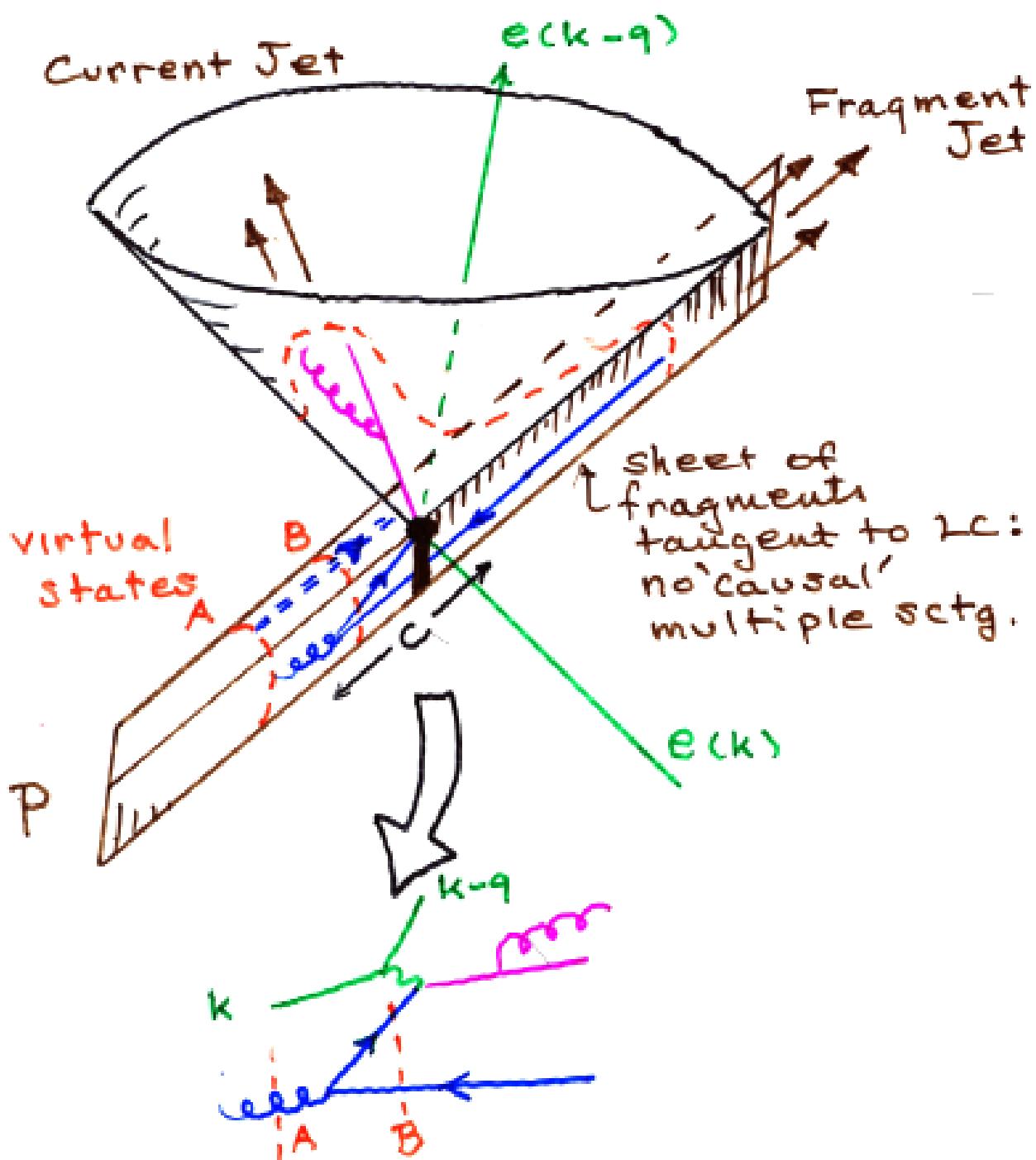
- new methods for light quarks, XSB
- confinement
- vary n_f (light)

QCD Phases: Other Vacua

- What else can we get?
- Thermodynamic parameters: T, B
- $B = 0, T \gtrsim 150 \text{ MeV}$
 $\langle \bar{q}q \rangle_{\text{LRG}} \rightarrow 0$
 chiral phase transition
- $T \sim 0, B \sim B_{\text{nuclei}}^* (?)$
 $\langle 0|q q|0 \rangle \neq 0$
 BCS-like color superconductivity
 from \mathcal{L}_I ~~X~~
 (at high B from magnetic interaction)
- Large T, B : plasma
 quark-gluon degrees of freedom



DIS: partons in hadrons



• Factorization

- QM incoherence of hard scattering from hadronic structure

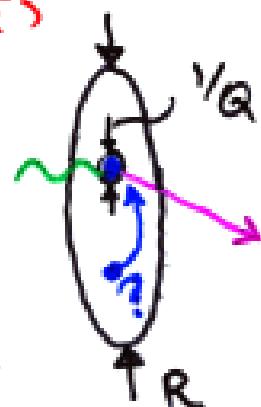
$$F(x, Q^2) = \left| \begin{array}{c} q \\ \text{---} \\ \text{---} \\ \text{---} \\ \text{---} \\ \text{---} \end{array} \right|_1 \left| \begin{array}{c} \text{---} \\ \text{---} \\ \text{---} \\ \text{---} \\ \text{---} \\ \text{---} \end{array} \right|_2 \quad Q^2 = -q^2$$

$$F(x, Q^2) = \sum_{a=G, q, \bar{q}} \int_x^1 d\xi \frac{\text{IR safe}}{C_a(\xi, \mu)} \frac{\text{factorization scale}}{\phi_{a,p}(\xi, \mu)} + \Theta(1/\alpha^2)$$

$\hookrightarrow x = \frac{Q^2}{2p \cdot q} \rightarrow m^2(\tau_m) \geq 0$

Corrections
from 'more
partons'
'higher twist'

$$\frac{\alpha_s(Q^2) \phi_{G,p}(x, Q^2)}{Q^2 R_p^2}$$



- normally: $\mu = \Theta(Q) \mapsto C_a$ from PT

expt. \mapsto measure $\phi_{a,p}(\xi, Q)$

• Factorization to Evolution

$$\mu \frac{dF}{d\mu} = 0 \rightarrow \mu \frac{d}{d\mu} \phi(\xi, \mu) = \int_{\Xi} dz P(\frac{\xi}{z}) \phi_s(\mu)$$

$\cdot \phi_b(z, \mu)$

(DGLAP)

$$P_{q/G}(\frac{\xi}{z}, \alpha_s) = \left| \begin{array}{c} \nearrow z^{5P} \\ \searrow z^{P_A} \end{array} \right|^2$$

- expands predictive power of pQCD

• Saturation: door to 'new' QCD

$$P_{G/G}(z) = \left| \begin{array}{c} \nearrow z^{8P} \\ \searrow z^P \end{array} \right|^2 \sim \frac{1}{z}$$

$x \rightarrow 0$ analysis sums logs
of z (BFKL)

Σ

$$x \phi_{G/p}(x, \mu) \sim \frac{1}{x^{\omega_{G/p}}}$$

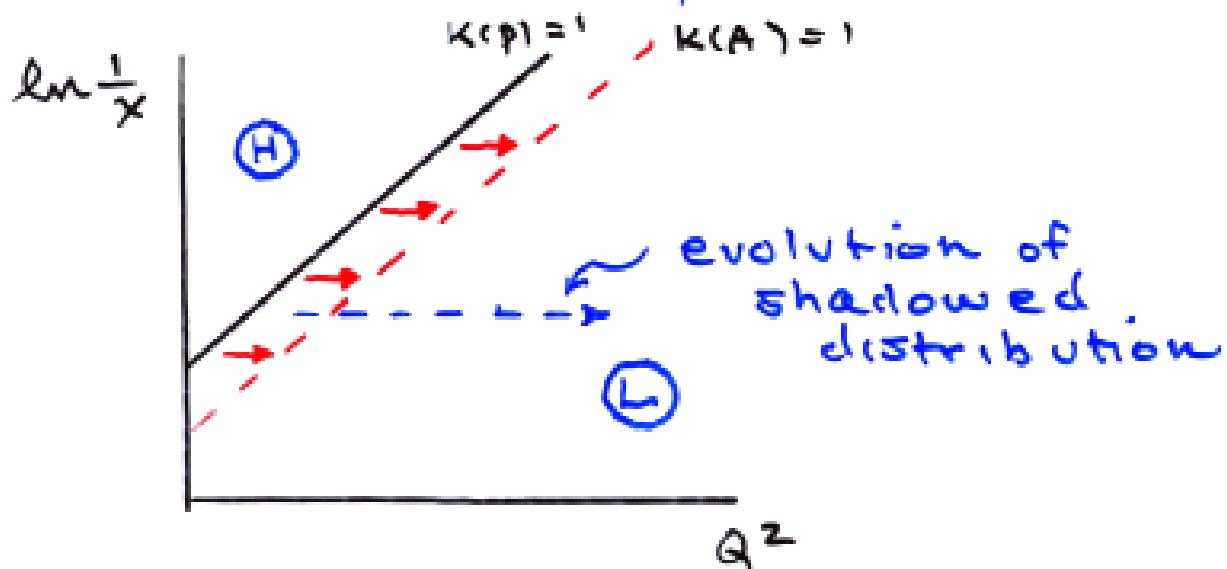
$x \rightarrow 0$ high G density

$\mu \gg \Lambda_{QCD}$ weakly itg.

saturation scale $\alpha_s \frac{\sigma(x, Q_0)}{Q_0^2 R^2} \sim 1$

(Low- x)

- The Evolution plane (GLR)



$$\kappa = \frac{3\pi^2 \kappa_s}{2Q^2} \left(\frac{x G(x, Q^2)}{\pi R^2} \right) \begin{cases} > 1 & \textcircled{H} \\ < 1 & \textcircled{L} \end{cases}$$

$\downarrow () \sim A^{1/3}$

$\kappa > 1$ all ~~Q^2~~ power corrections

contribute: new evolution

BFKL

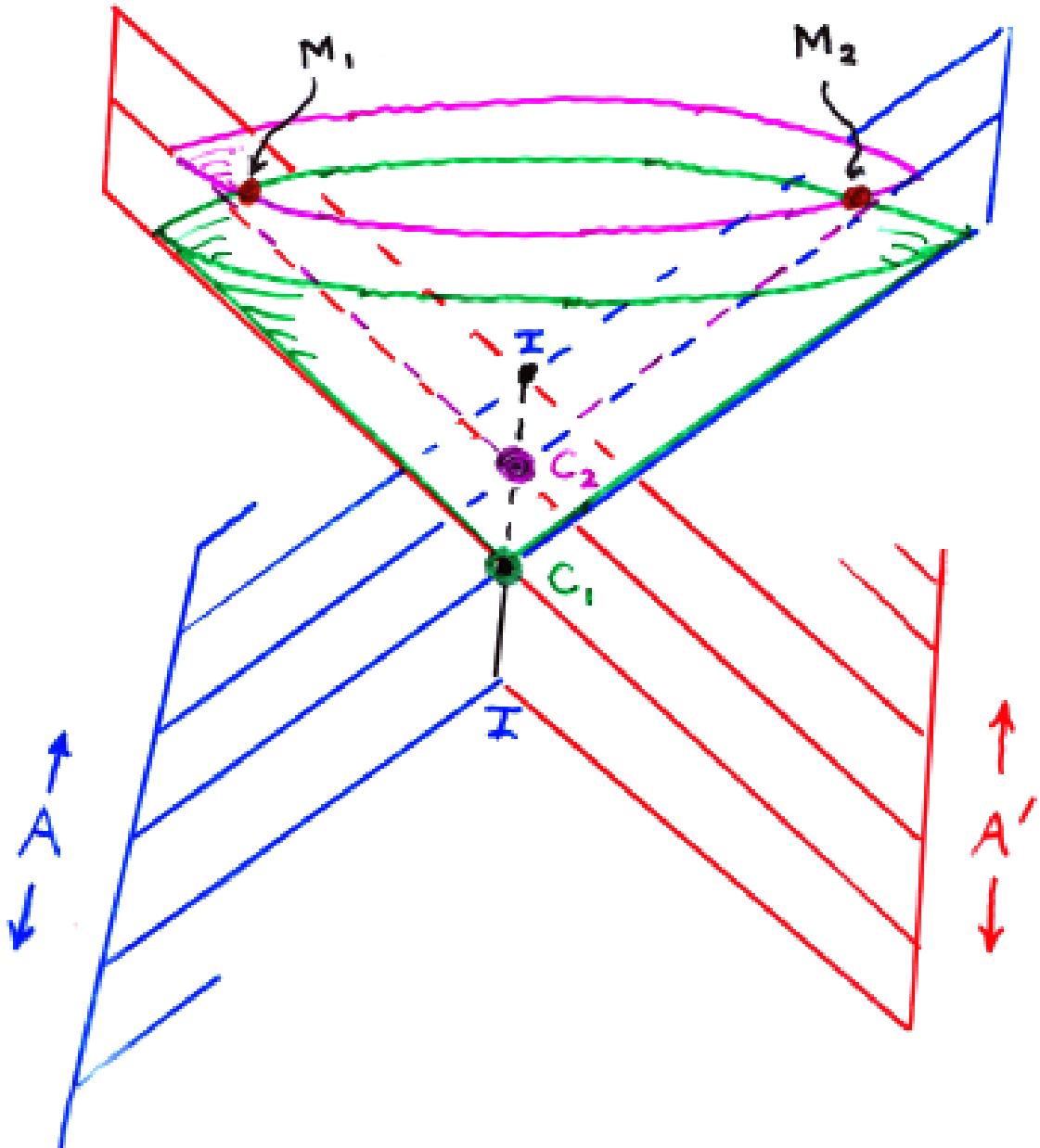
Balitsky, Kovchegov
McLerran,

Yengopalan

\textcircled{H} $\kappa > 1$: Saturation

\textcircled{L} $\kappa < 1$: Shadowing = influence
of A -dependence of $k=1$
line Moeller, Qiu

AA' : From low- x to high density



- Line I - initial condition
partons of both nuclei overlap
- M_1, M_2 causally connect points
 C_1, C_2 on line $I \rightarrow$ multiple scattering

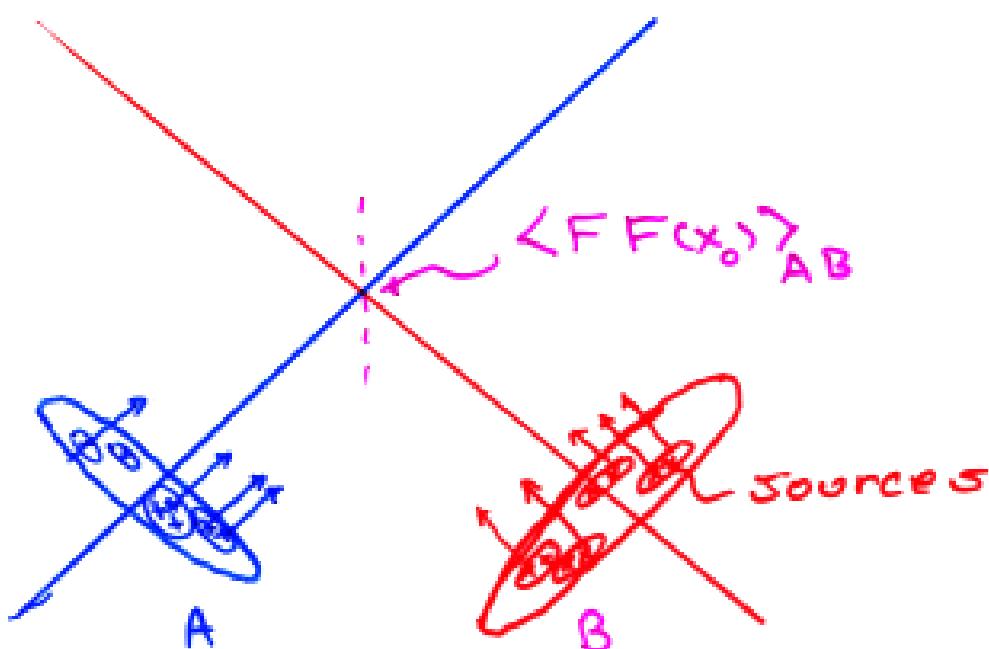
Initial Conditions

- High- E_{cm} : even low- x gluons carry substantial energy
- Model for large nuclei

$$H_{\text{nuclear}} = H_{\text{QCD}} + \frac{i}{N_c} \int d^2x_t dx^- \rho(x_t, x^-) \\ \cdot W_+(x^-, x_t)$$

ρ : distribution of sources
(random for $A \rightarrow \infty$)

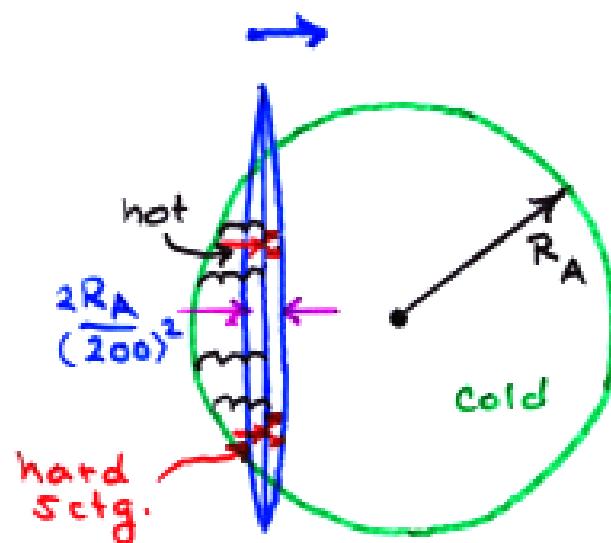
$$W_\pm = P \exp \int_{-\infty}^{\infty} dx^\pm A^\mp(x)$$



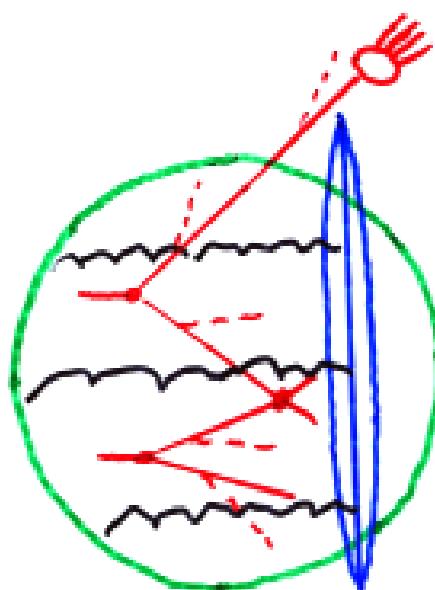
⇒ CLASSICAL STRENGTH $\langle FF(0) \rangle \sim \frac{1}{\alpha_s(Q_s)}$
AT INITIAL STATE

ENVIRONMENT FOR AA HARD SCATTERING

- AA collision in 'target' rest frame

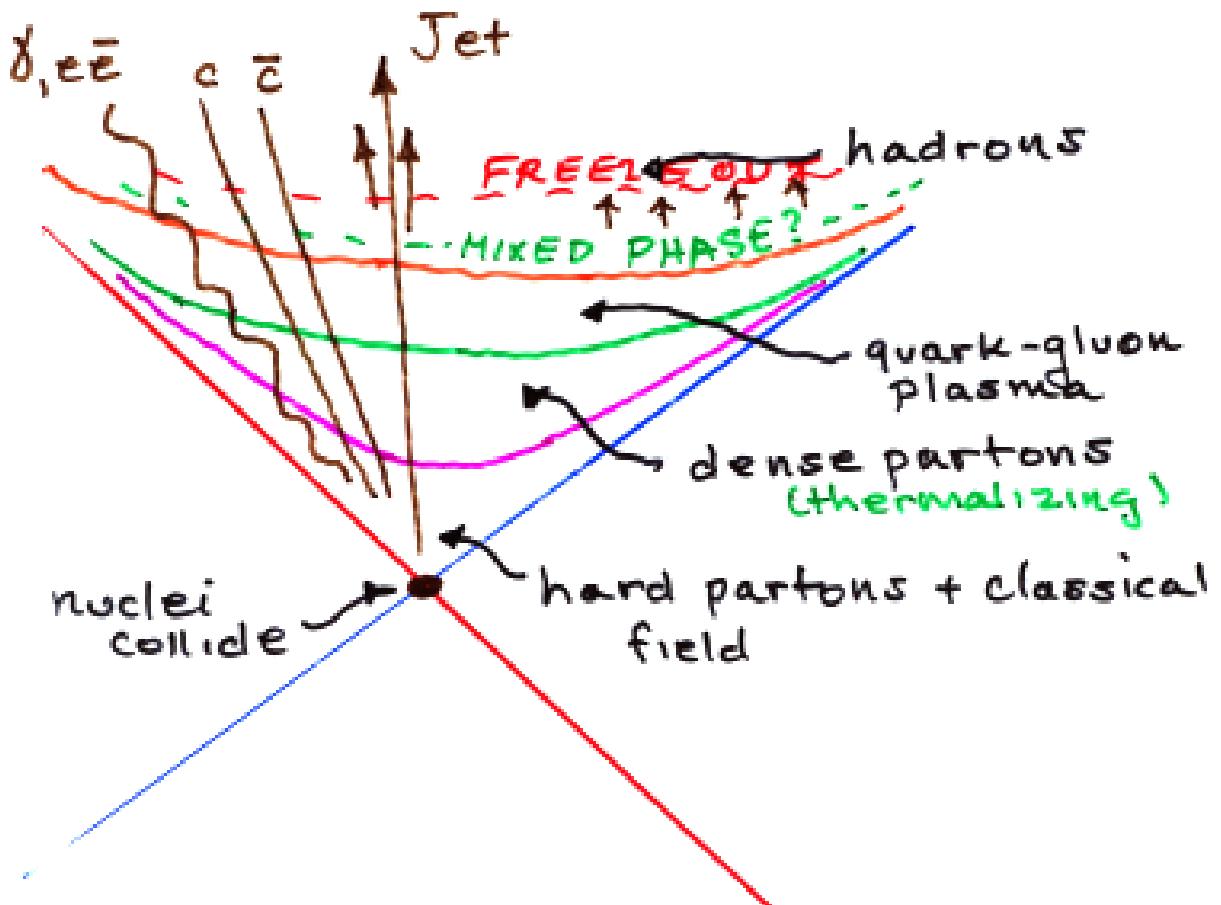


- ISI, and
Hard Scat:
'cold'



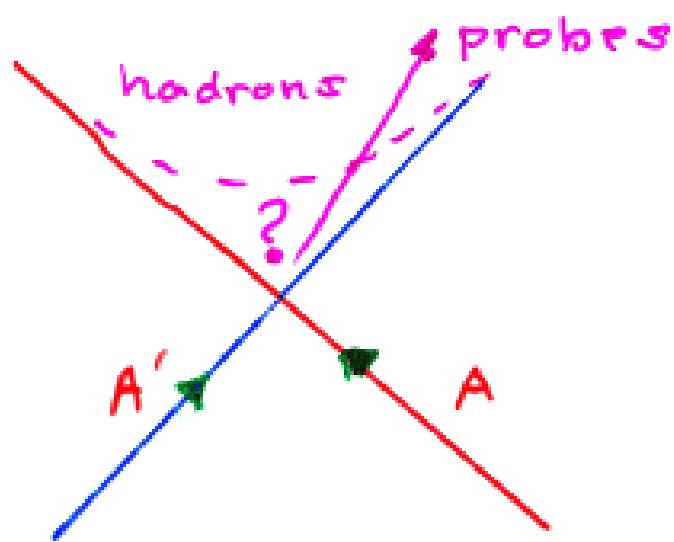
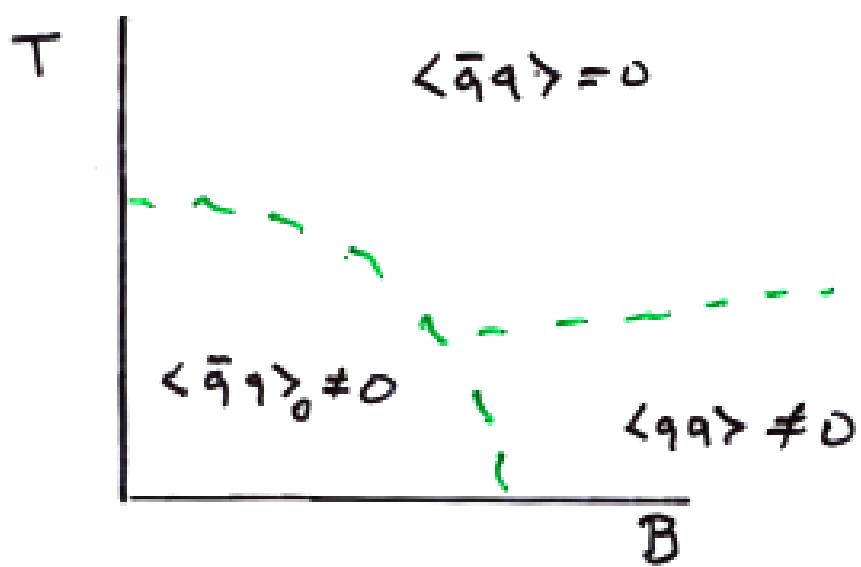
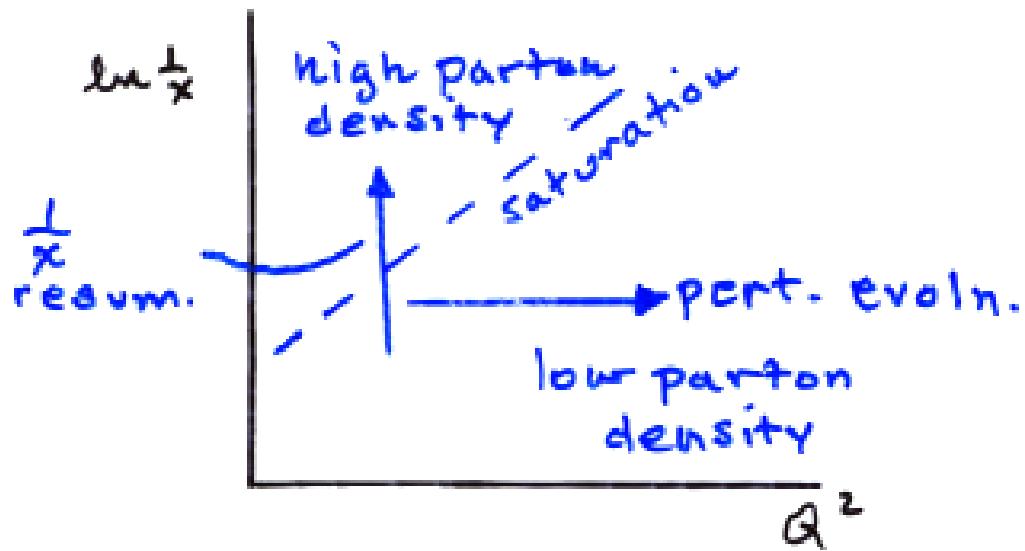
- FSI
'hot'
- Small angle/
hadronization
'vacuum'

- Plausible history: probes of early times



- Probes, diagnostics
 - jets: energy loss
 - 'LPM' analysis: multiple scattering
 - enhances radiation with short formation time
 $\Delta E \propto L^2$
 - suppresses radiation with long formation time
 - $c\bar{c}$: J/4 suppression
 - strange hadrons: enhanced by 'ξ restoration'
 - $\gamma e\bar{e}$: charged particles at early times
 - hadrons: correlations, fluctuation at 'freeze-out'

SUMMARY



NO CONCLUSIONS
HERE...

QCD: A YOUNG THEORY

ENJOY THE CONFERENCE!